2015 SCEC Report

Proposal Number: 15030

Joint seismotectonic and source spectra analysis of the Ventura Basin and San Gorgonio Pass SCEC Special Fault Study Areas, southern California

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Category:
B. Integration and Theory & C. Special Fault Study Area

Science objectives: 1a, 2d, 4d

Focus areas: EFP, SoSAFE, USR

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Abstract

The 2015 Fillmore swarm occurred about 6 km west of the City of Fillmore in Ventura, California, and was located beneath the eastern part of the actively subsiding Ventura basin at depths from 11.8 km to 13.8 km, similar to two previous swarms in the area. Template-matching event detection showed that it started on the 5th of July 2015 at 2:21 UTC with a ~M1.0 earthquake. The swarm exhibited unusual episodic spatial and temporal migrations, and diversity in nodal planes of focal mechanisms as compared to the simple hypocenter defined plane. It was also noteworthy because it consisted of >1,400 events of M≥0.0, with M2.8 being the largest event. We suggest that fluids released by metamorphic dehydration processes, migration of fluids along a detachment zone, and cascading asperity failures caused this prolific earthquake swarm. Other mechanisms such as simple mainshock-aftershock stress triggering or a regional aseismic creep event are less likely. Dilatant strengthening may be a mechanism that causes the temporal decay of the swarm as pore pressure drop increased the effective normal stress, and counteracted the instability driving the swarm.

Our analysis showed differences in stress drop characteristics between the San Gorgonio Pass (SGP) and Ventura (VB) Special Fault Study Areas. The SGP has significant internal variation in stress drop magnitudes, and also exhibits systematically higher stress drops than does VB. We demonstrate that the higher scatter in SGP is not a generic artifact of our method but an expression of underlying differences in source processes. Our results suggest that higher ambient stresses, which can be deduced from larger focal depth and more thrust faulting, may only be of secondary importance for stress drop variations. Instead, the general degree of stress field heterogeneity and strain localization may influence stress drops more strongly, so that more localized faulting and homogeneous stress fields favor lower stress drops. In addition, higher regional loading rates, for example, across the VB potentially result in stress drop reduction whereas localized slow loading rates on structures within the SGP result in anomalously high stress drop estimates.

SCEC Annual Science Highlights

Our research this past year involved two complimentary efforts – the first an assessment of the 2015 Fillmore earthquake swarm in the Ventura basin, and the second a regional assessment of earthquake stress drop characteristics in the Ventura and San Gorgonio Special Fault Study Areas (SFSA's).

Exemplary Figure: See Figure 1

SCEC Science Priorities: 1a, 2d, 4d

Intellectual Merit

This project relates to many key SCEC objectives and will improve our understanding of earthquake activity across southern California. In particular, our high-resolution studies of seismicity provide better delineation of fault structures and make possible more advanced seismicity studies by us and other SCEC researchers. Our analyses provide fundamental insights into micro-earthquake activity, the crustal strain field, major faults, and crustal geophysics.

Broader Impacts

The outreach activities consisted of publishing the results of the research in peer-reviewed journals. Also, the focal mechanism catalog is being distributed to researchers via the Southern California Earthquake Data Center (SCEDC). We have also presented results at SCEC workshops.

Project Publications

Goebel, T. H. W., E. Hauksson, A. Plesch, and J. Shaw, Detecting significant stress drop variations in large micro-earthquakes datasets: A comparison between a convergent step-over in the San Andreas Fault and the Ventura thrust fault system, southern California; Special Volume of *Pure and Applied Geophysics*; submitted, January 2016.

Goebel, T. H. W., E. Hauksson, A. Plesch, and J. Shaw (2014), A comparative study of Seismotectonics in the San Gorgonion and Ventura Special Fault Study Areas, *Southern California Earthquake Center Annual Meeting, Proceedings and Abstracts*, **24**.

Goebel, T. H. W., E. Hauksson, J.-P. Ampuero, and P. M. Shearer (2015), Stress drop heterogeneity within tectonically complex regions: A case study of San Gorgonio pass, Southern California, *Geophys. J. Int.*, doi:GJI-S-14-0861, (in revision).

Goebel, T. H. W., E. Hauksson, P. M. Shearer, and J. P. Ampuero (2015), Stress-drop heterogeneity within tectonically complex regions: A case study of the San Gorgonio Pass, southern California, *Geophys. J. Int.* **202**, 514–528 doi: 10.1093/gji/ggv160

Hauksson, E., J. Andrews, A. Plesch, and J. H. Shaw, D. R. Shelly, The 2015 Earthquake Swarm Near Fillmore, California: Possible Dehydration Event Near the Bottom of the Over-Pressurized Ventura Basin*, in review*, *Seismological, Res. Letters*, Feb., 2016

Hauksson, E. (2014), Average stress drops of southern California earthquakes in the context of crustal geophysics: Implications for fault zone healing, *Pure Appl. Geophys.*, pp. 1–12, doi:10.1007/s00024-014- 0934-4.

Technical Report

The 2015 Fillmore Earthquake Swarm, eastern Ventura Basin, California

Earthquake swarms that occur in a variety of tectonic settings in southern California can be characterized by onsets ranging from gradual to fast, lack of a prominent mainshock, and different styles of migration over time and space (e.g. Vidale and Shearer, 2006). Tectonic swarms are often interpreted as being either related to movement of fluids in the crust and in some cases related to aseismic creep events causing localized changes in stress (Roland and McGuire*,* 2009).

The greater Ventura region is characterized by an elevated rate of background seismicity that is in part driven by rapid tectonic convergence (~7 mm/yr) in the region (Marshall *et al.,* 2013). Background seismicity from 1981 to 2015, with average rate of ~5 M≥3 events per year, is mostly located on the north side of the Ventura basin (Figure 1). In contrast the 2015 Fillmore swarm provided a unique opportunity to study tectonic deformation processes at depth below the basin sediments. In particular, the recorded seismicity may reflect geological processes at depth including release of fluids caused by metamorphic dehydration (Ague *et al.,* 1998), fluid migration as well as cascading asperity failures along a detachment zone.

The east-west trending Ventura basin is the deepest of several Cenozoic sedimentary basins in the Transverse Ranges province of southern California (Yeats*,* 1976). The eastern half of the basin is bounded by the San Cayetano fault to the north and the Oak Ridge fault to the south (Figure 1). The ongoing subsidence and infill of sediments in the Ventura basin suppresses the crustal isotherms and results in low heat flow, as low as 43 mW/m^2 (DeRito *et al.,* 1989). The suppressed isotherms in the Ventura region are also consistent with unusually deep seismicity beneath the basin (Bryant and Jones, 1992). Both mainshock-aftershock sequences and small swarms occur down to depths of 25 to 30 km.

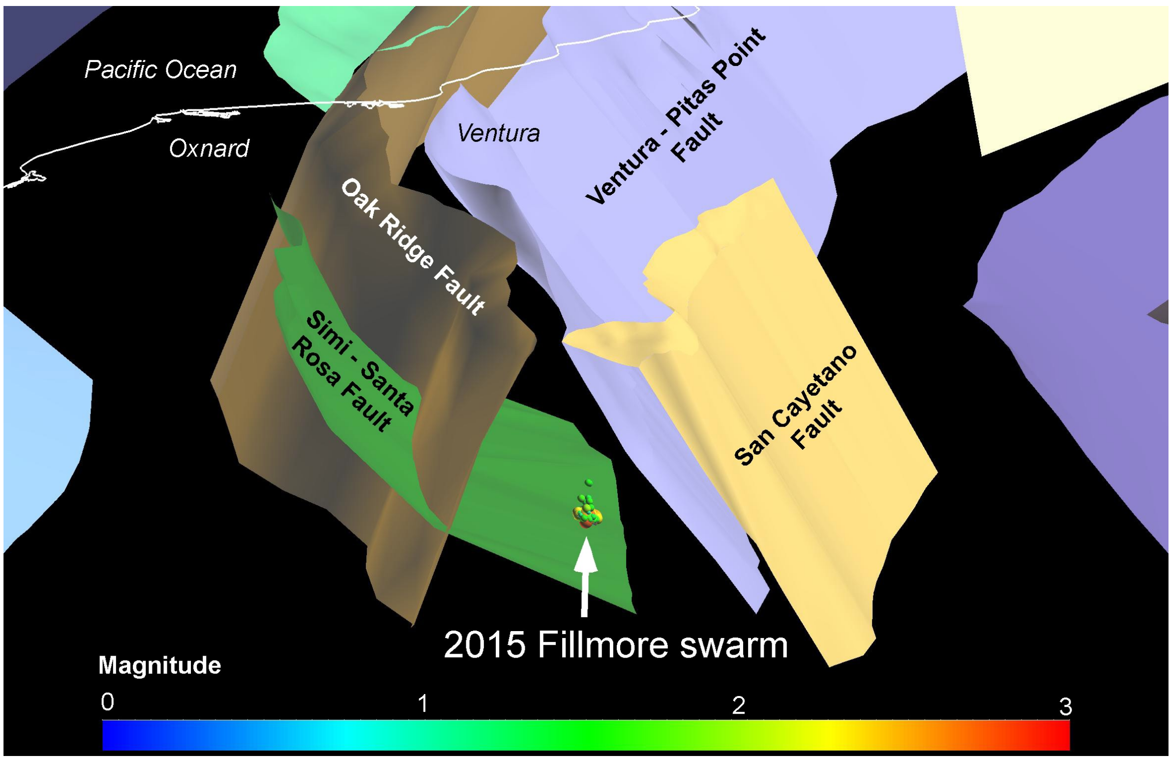

Figure 1. (Exemplary Figure). A perspective view looking west of the Ventura basin and Fillmore swarm. The different color surfaces are major late Quaternary faults represented in the SCEC Community Fault Model (CFM (Plesch et al., 2007). The coast line is shown as a white jagged line. Hypocenters for the 2015 Fillmore swarm are highlighted by magnitude, and occur along the down-dip extent of the Simi-Santa Rosa fault zone Nicholson et al., (2014).

Previously, Vidale and Shearer (2006) identified 71 earthquake clusters in southern California with each consisting of more than 39 earthquakes. They analyzed spatial, temporal, and magnitude features of these 71 earthquake clusters, and showed that 19 sequences were swarm like. They favored pore fluid pressure fluctuations as the mechanisms most likely responsible for seismicity bursts, although they suggested that in some cases aseismic slip could play a role. In addition, Chen and Shearer (2011) studied earthquake swarms in the Salton Trough area and obtained a similar hydraulic diffusion coefficient of ~0.25 m^2/s for the Salton Sea geothermal area. They found migration velocities from 0.008 to 0.8 km/hour, and argued that if the migration velocities exceeded 0.1 km/hr, fluid diffusion is not rapid enough and other processes such as creep or slow slip events are required to explain the seismicity.

Two other small earthquake swarms have occurred in the Ventura region since improved seismic monitoring became available in 1981. First, a swarm of 50 earthquakes of M1.2 to M1.8 occurred near the southeast corner of the basin, about 8 km south-southeast of Fillmore, in May 1989. It exhibited similar spatial and temporal behavior as the 2015 swarm (Shearer*,* 1998). Second, Chen *et al.* (2012) also identified a comparable swarm in 2000, located adjacent to the 1989 Oak Ridge swarm.

Our high-resolution seismological study involves a very small crustal volume of 1.5 km by 0.5 km by 2 km. When compared with a 90 km long 1992 Mw7.3 Landers rupture this cluster would be a mere dot on an aftershock map, and therefore the swarm does not contribute significantly towards understanding the broader regional tectonics. However, because the SCSN seismic station density is higher than in the past, and the digital data are of higher quality, we are able to apply new data analysis techniques to resolve intricate spatial and temporal details of the crustal deformation processes and explore the possible driving mechanisms for such sequences. In summary, we find that the 2015 Fillmore swarm consisted of >1,400 events of M≥0.0, with M2.8 being the largest event. The swarm exhibited unusual episodic spatial and temporal migrations, and a diversity in nodal planes of focal mechanisms. These nodal planes were generally inconsistent with the simple plane defined by the hypocenters, which corresponds closely with the Simi-Santa Rosa fault zone (SSRF) as described by Nicholson *et al.* (2014) and included in the SCEC CFM (Plesch et al., 2007). We suggest that fluids released by metamorphic dehydration processes, migration of fluids along a detachment zone, and cascading asperity failures caused this prolific earthquake swarm. *For more details see: Hauksson et al. (2016).*

Comparing Earthquake Stress Drops in San Gorgonio and Ventura, California

The comparative analysis of stress drop variations in VB and SGP showed that stress drop estimates of individual earthquakes can vary strongly over up to three orders of magnitude. This scatter may not solely be due to measurement uncertainty but rather indicate real-variations in stress drop values. To confirm these results, we test whether statistical significant stress drop variations are resolvable in large (>100s earthquake) sample sizes. First, we smoothed spatial representations of stress drop estimates and binned depth variations. Second, we examine the robustness of stress drop variations by analyzing corner frequency and seismic moment estimates as well as spectral shapes of stacked source terms.

The smoothed spatial variations in individual event stress drops show large variation in SGP ranging from 1 to more than 20 MPa, compared to VB where stress drop estimates are between 0.5 to 2 MPa throughout the study area (Figure 2). The smoothed maps were computed from individual event stress drops and by using regional EGFs in VB and SGP to correct for high-frequency attenuation prior to fitting a Brune-type model to the source spectra. Stress drop values were then smoothed using the log-normal mean of the 200 closest events. The smoothed stress drop map in SGP reveals a region of significantly elevated stress drops with values above

20 MPa with decreasing stress drops down to 1 to 4 MPa to the south and north of this area. The region is located between the San Gorgonio thrust and Mission Creek fault and coincides with a 'structural knot' in the San Andreas fault system (e.g. Langenheim et al., 2005; Dair and Cooke, 2009). The VB region shows less variation about the average value of 1 MPa with the 5th and 95th percentile occupying values of 0.3 and 3.4 MPa. Slightly elevated values of ~2 MPa can be observed in the Malibu coastal area.

Even though our study regions in VB and SGP host some of the deepest seismicity in southern California, we observe limited evidence for systematic variations of stress drops with depth. We computed average stress drops in 2 and 4 km depth-bins in SGP and VB and report the log-mean stress drop as well as 10th and 90th percentiles (Figure 2). In SGP, stress drop estimates are largely constant within the upper 8 km and show a sharp increase at ~9 km from ~3 MPa to ~6 MPa. In the VB, stress drops increase systematically as a function of depth from 0.5 to 1 MPa. This increase may partially be due to increasing rupture velocities with depth which can be tested by using a 1D shear-wave velocity model for Southern California and by assuming that variations in shear-wave velocities are a good proxy for rupture velocity variations. The apparent increase in stress drop with depth is reduced to $\Delta\sigma$=0.7 MPa at 2 km and $\Delta\sigma$=0.9 MPa at 18 km depth. Thus, we conclude that, although there is an abrupt increase in stress drop below 10 km in SGP, there is no generic relationship between stress drop and focal depth.

We also examine the role of shear wave velocity variations as a proxy for rupture velocity changes at each hypocenter using the 3D CVM-H velocity model for Southern California (Shaw et al., 2015). The 3D model includes a more gradual increase in seismic velocities with depth in VB compared to SGP. However, the strongest changes in velocities are concentrated in the upper 5 km above the seismically most active depths. Using the 3D velocities as input in Equ. 3, we find that average stress drop increase to 1.12 MPa in VB and decrease down to 4.7 MPa in SGP. For velocity changes to account for the entire difference in stress drops between the two study regions an average difference in velocities of 1.5 km/s would be required between the two regions across all depths, which is generally not observed.

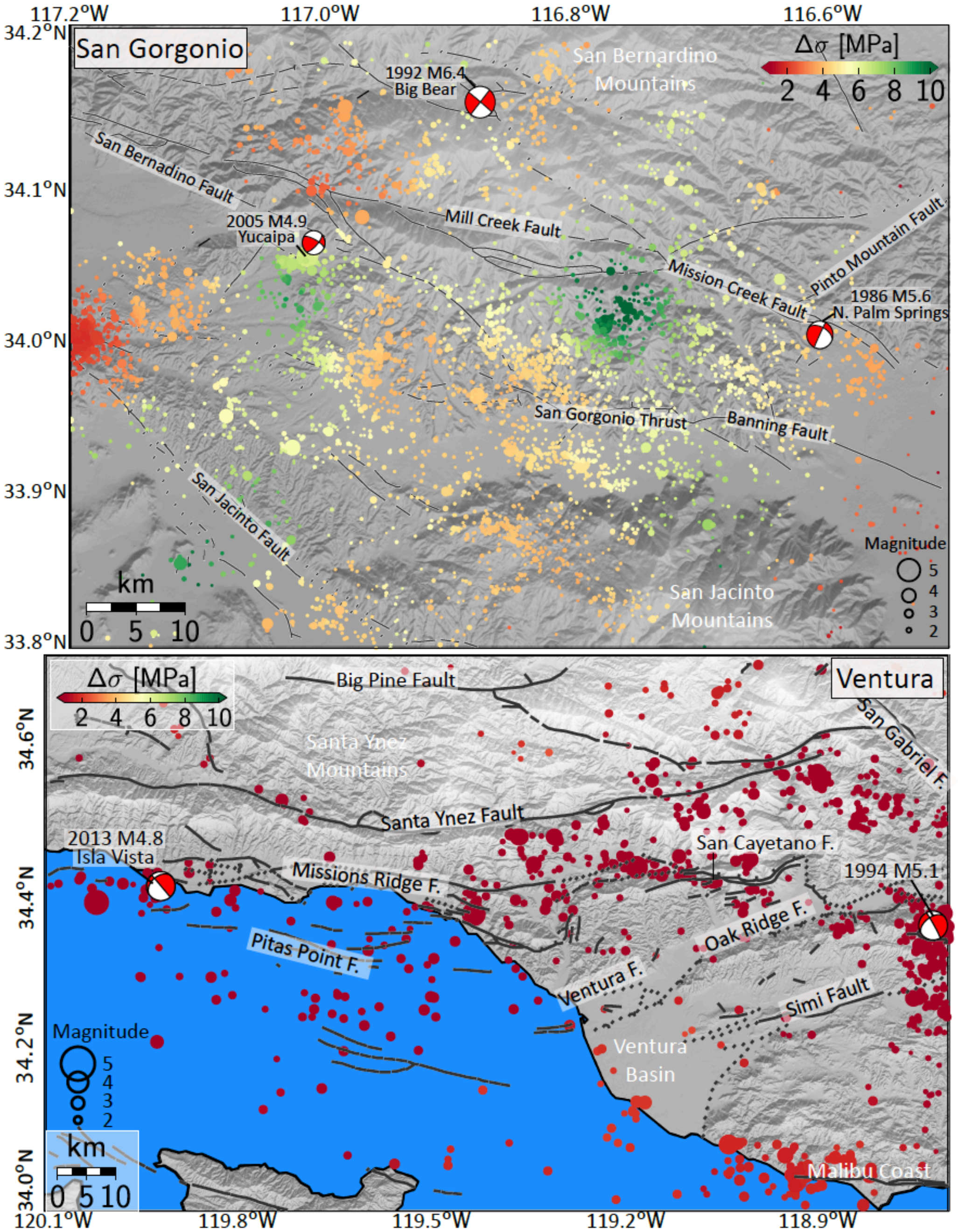

Figure 2: Smoothed spatial variation in stress drop estimate using the log-normal mean of the 200 closest events in SGP and VB. Stress drop estimates vary substantially in SGP between 1 to 20 MPa whereas stress drops in VB are uniformly close to 1 MPa (See legend in upper right for stress drop values corresponding to marker colors)

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